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14. ABSTRACT
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Mine Burial by Scour: Results from the Gulf of Mexico Experiments

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Abstract: A 64 day experiment to characterize mine burial by scour was conducted in the winter of 2003 in water depth of 13 meters off Indian Rocks Beach (IRB) near Tampa Bay, Florida. Instrumented and non-instrumented mines were located on both coarse and fine sand sediments. In addition to monitoring the mine burial (16 mines) the experiment included, measurements of sediments properties and oceanographic conditions, and a comparison of model prediction to measure burial. Mine burial, relative to the water-sediment interface, by scour occurred during storm events (defined by significant wave heights greater than 2 meters). Following the second storm event burial of the mines on fine sand sediment exceeded 50% (and to 100% in some cases) whereas the mines on coarse sand sediment had buried little to none. Mine burial predictions based upon a wave induced scour model were nearly identical to the measured mine burial.

I. INTRODUCTION

Buried mine detection is one of the greatest challenges facing shallow water Mine CounterMeasures (MCM) operations [1]. The possible presence of buried mines can change MCM tactics from one of mine hunting to one of minesweeping or area avoidance. The ability to predict mine burial both for planning and during operations (strategic and tactical scenarios) is therefore of great importance to Naval forces. Processes known to contribute to mine burial include burial at impact usually in low strength muddy sediments; scour and fill; bedform migration or transverse bedform movement; bedform morphological alterations, such as changes to shorerise or bar-berm conditions; liquefaction or fluidization of the sediment; and biological processes that scour or promote scour by altering seafloor physical proper [2].

ONR initiated a multi-year (FY01-05) interdisciplinary

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program of research designed to improve the state of the art in mine burial prediction (T. Drake et. al., Sixth International Symposium on Technology and the Mine Problem). This Mine Burial Prediction basic research program integrates field, laboratory, and statistical studies with theoretical modeling to advance the state-of-the art in mine burial prediction. The Indian Rocks Beach experiment focused on the complex coupled interaction of environmental forcing on the seafloor-mine system by waves, currents, and tides.

Fig. 1. Overall view of the Experiment Site. The site selected for the Winter 2003 mine scour and burial experiments is located in 12-15 m water depth. Filled green circles indicated approximate locations of sensor deployments. High backscatter is dark (100 kHz side scan data).

II. DESCRIPTION OF THE EXPERIMENT

The experiment included mine burial studies (16 mines), measurement of sediment properties and oceanographic conditions, mine burial predication and comparison of model predications and mine burial. Briefly, field work for the IRB Winter 2003 experiment involved deployment and visual inspection of 16 different mines and mine shapes at three different sites, collection of sediment samples for laboratory analysis (Fig. 1), visual and acoustic monitoring of mine burial and seafloor characteristics using video cameras attached to ROVs, diver photography and multibeam and side scan sonar. Oceanographic conditions were monitored using USF's instrumented quadpod. Table 1 includes a list of the mines deployed at each site and physical properties of sediments collected near the mines.

III. THE MINES

The Acoustic Instrumented Mines (AIMs) were developed by the Naval Research Laboratory (NRL) and Omni Technologies, Inc. (Fig. 2). These Instrumented Mines are constructed of Naval Aluminum Bronze and measure both the processes that initiate and affect burial and mine burial behavior. The AIMs use 112 acoustic burial sensors mounted flush with the mine surface to measure burial and dimensional characteristics of the scour pit. Roll, pitch, and mine heading are measured with accelerometers and electronic compasses. Accelerometers (3-axis) are used to

Table 1. List of mines and core results at each site.

Mine	Nearest Core		
	Depth (cm)	Porosity (%)	Bulk Density (g/cm^3)
Site 1 - Fine Sand Sediment			
AIM #1*	0-11	42.02	1.999
AIM #2*	0-18	39.38	2.019
AIM #3*	0-12	40.18	2.015
AIM #4*	0-22	41.56	1.984
FWG #5*	0-8	44.28	1.941
FWG #6*	0-9	38.39	2.041
Manta #12*	0-8	32.97	2.129
Rockan #14*	0-8	37.85	2.053
Bomb #16*	0-8	40.9	2.001
Site 2 - Coarse Sand Sediment			
FWG #7	0-10	45.72	1.956
FWG #8	0-8	36.4	2.091
Manta #11*	0-10	39.72	2.034
Rockan #13	0-11	40.71	2.023
Bomb #15	0-12	45.09	1.97
Site 3 - Fine Sand Sediment			
FWG #9*	0-16	40.39	2.012
FWG #10*	0-7	45.63	1.92

* Core from pit left by mine.

detect mine motion that occurs as a result of the mine falling into a scour pit or of the seafloor liquefying. Pressure sensors measure bottom pressure fluctuations associated with tidal changes and surface gravity waves. Coherent acoustic Doppler sensors have been added to two of the AIMs, to measure hydrodynamic flow rates around the mines. Flow rates (mean and instantaneous) can be calculated from the Doppler sensors and sediment concentration values can be calculated from acoustic backscatter of the burial sensors and then can be used to estimate rates of sediment transport. The AIMs orientation sensors consists of a commercial off-the-shelf 3-axes flux gate compass and 3-axes accelerometer for roll and pitch. Heading accuracy is approximately +/- 2.0° and roll/pitch accuracy is approximately +/- 0.5°. The selection of a non-magnetic housing allows use of a magnetic heading sensor as opposed to a fiber optic compass. A 3-axis accelerometer continuously monitor accelerations associated with mine movement such as rocking and falling into scour pits and sinking during liquefaction. These sensors are located near the geometric center of the mine and movement associated with accelerations greater than 0.1 G triggers a storage sequence whereby pre and post trigger accelerations are recorded. Additional technical details on the AIMs are available in reference [1 and 3].

The FWG Instrumented Mines were developed in the early 1970s by Ingo Stender of FWG in Kiel, Germany. These mines are self-recording and use optical methods to detect the

mine burial state [4] (Fig. 3). Burial is measured by three rings of 24 paired optical sensors externally mounted at even intervals (15°) around the mines. Transmitting optical sensors are LED's and receiving optical sensors are phototransistors. Burial is detected by blockage of these sensors. Roll and pitch is determined with a similar system as used in the NRL AIMs. For this experiment the sample rate (for each FWG mine) to detect sensor burial and orientation was set at 15 minutes. Thomas Wever and Ralf Lühder, both of FWG, prepared these instrumented mines and oversaw their deployment, recovery and initial data analysis.

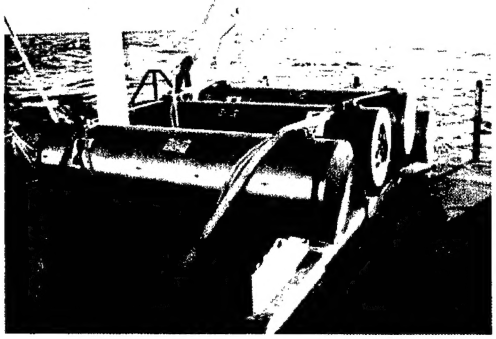

Fig. 2. Four NRL Acoustic Instrumented Mines (AIMS).

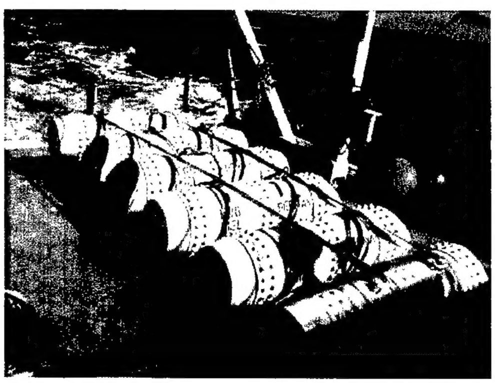

Fig. 3. Six FWG Instrumented Mines.

The non-instrumented Inert Mines included three different types. The Italian Manta bottom mine and Swedish Rockan mine (Fig. 4 and 5) are fairly sophisticated weapons that are laid on the ocean floor and set off by a ship's magnetic, acoustic, or pressure signature. Both the plastic-shelled Manta and the wedge-shaped plastic-shelled Swedish Rockan GMI-100 are current examples of reduced-signature mines that are designed to be difficult to detect acoustically. Two inert MK-82 general purpose (GP) 500-pound iron bombs (normally used in a free-fall, nonguided configuration) were also included as part of this experiment (Fig. 6).

IV. SEDIMENTS

Sediments were sampled by divers using 6.1-cm-diameter cores that were pushed into the top 12-23 cm of sand. In January during the mine deployment phase cores were collected north and south, but proximal to, mines # 1, 2, 3, 4, 5, 6, 9, and 10. A single core was collected proximal to mines # 7, 8, 11, 12, 13, 14, 15, and 16. In March during the recovery phase cores were collected in the scour pits of mines # 1, 2, 3, 4, 7, 8, and 13. A core was collected from the pit in which the mine had been sitting for each mine except mines # 7, 8, and 13. In addition, two cores from each of the three sites were collected.

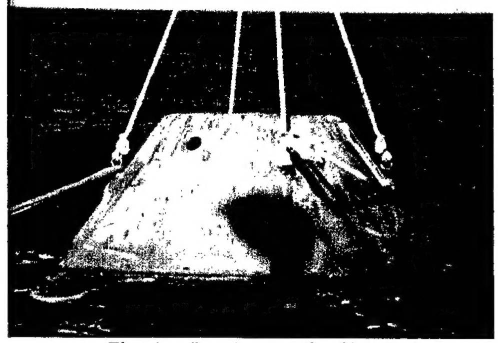

Fig. 4. Inert Manta Mine Shape.

Fig. 5. Inert Rockan Mine Shape.

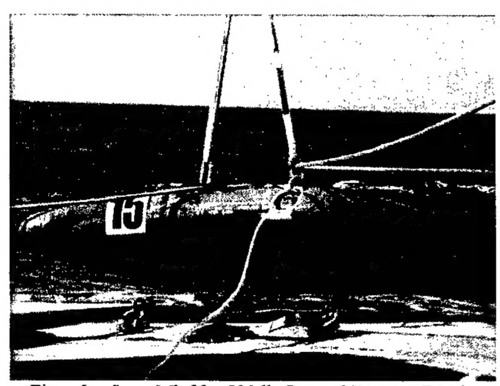

Fig. 6. Inert Mk 82 - 500 lb General Purpose Bomb.

Cores were acoustically logged at 200 and 400 kHz within 24-72 hours. The equipment and technique used to log the cores is described in [5]. After the cores were transported to shore, and subsequent to acoustic logging, the cores were assayed for water content, either in 2-cm sections or in their entirety. Samples were dried in a drying oven for 24 hours at 105°C, cooled in desiccators, weighed, and preserved in sealed plastic bags for further analyses of average grain density and grain size distribution [6].

Vertical distribution of sediment porosity measured on 15 of the 23 cores collected at the mine deployment is displayed in figure 7. Note that core 4N is slightly anomalous when compared with the other samples collected from fine sand (lower porosity). Sediment porosity for the six cores sectioned from the 25 cores collected during the mine recovery is shown in figure 8.

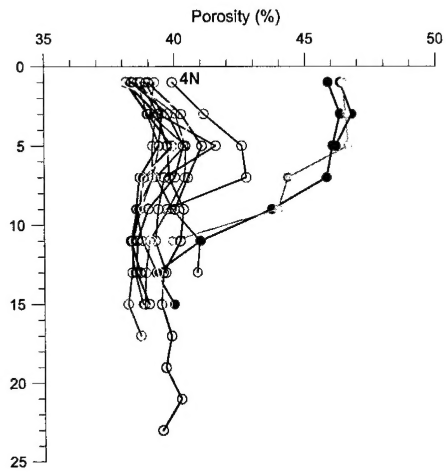

Fig. 7. Vertical distribution of sediment porosity measured on cores collected during deployment.

Three cores collected during the mine deployment were analyzed for grain size distribution and the variation in mean grain size as a function of depth in the sediment is presented in figure 9. The mean grain size of the fine sand at site 1 and 3 was approximately 0.15 mm. The mean grain size of the coarse sand at site 2 was approximately 0.70 mm. Fine sediment was well sorted quartz sand; coarse sediment was predominantly carbonate shell hash resulting from abrasion and weathering of mollusk shells. These data indicate that the coarse sand overlies the fine sand and that the coarse sand is about 12 cm thick.

V. OCEANOGRAPHIC CONDITIONS

Each AIM contains six pressure sensors to monitor changes in bottom water pressure fluctuations (0 to 100 psi at 10 Hz) and to provide input to calculate mean water depth and surface gravity wave height and period. Figure 10 displays water temperature, tides, wave period and significant wave height recorded at AIM #1 and is representative of the data from each of the AIMs. Note that the four AIMs were located within approximately 60 meters of each other and we would expect the very similar oceanographic conditions to be measured. The significant wave height indicates storm events on day dates 18, 24/25 and 55 (18 January, 24/25 January and 24 February respectively).

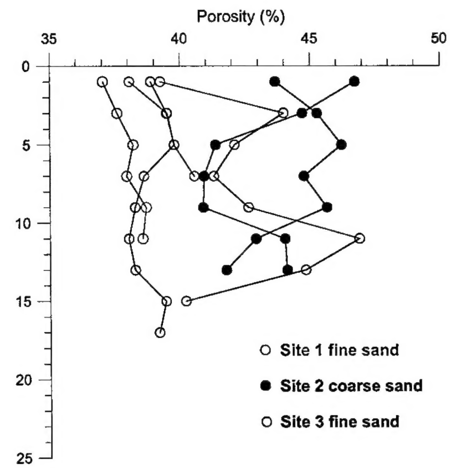

Fig. 8. Vertical distribution of sediment porosity measured on cores collected during recovery

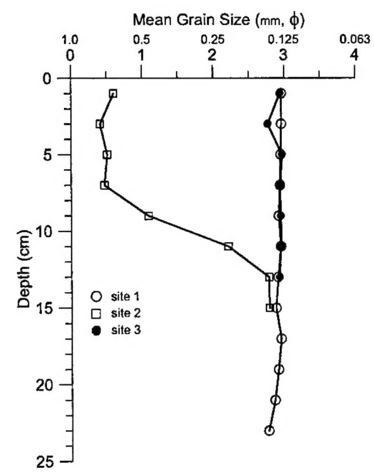

Fig. 9. Variation in mean grain size as a function of depth in the sediment.

Environmental conditions as collected by the USF instrumented quadpod at site 1 correspond to the

environmental data collected by AIM #1 (Fig. 10 and Fig. 11).

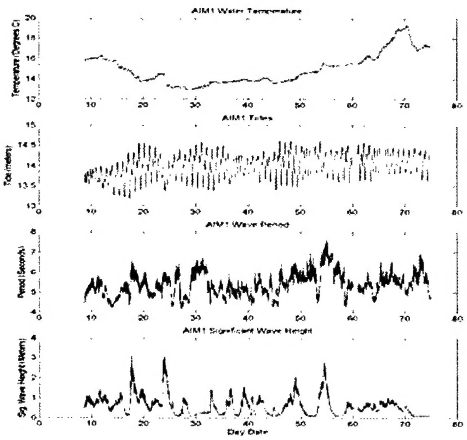

Fig. 10. Oceanographic Environment as measured by AIM #.1

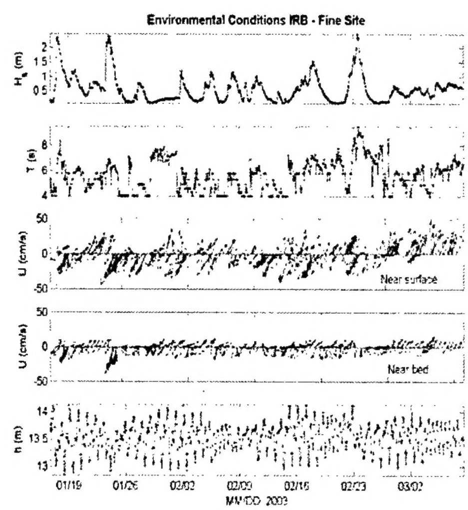

Fig. 11. Oceanographic Environment at Site 1 as measured by USF's Instrumented Quadpod. H is significant wave height, T is average wave period (not peak), U is orbital velocity (near surface is 10.5 m above bottom - near bed is 0.65 m above bottom), h is water depth. Storm events 1, 2 and 3 are clearly indicated on H (significant Wave Height) - 18 January, 24/25 January and 24 February respectively

VI. ORIENTATION

a. AIMs Orientation. Motion before, during and after events provides insight into the burial process. Burial, hydrophone and flow sensors also require orientation information to compare successive measurements for transformations to a common coordinate system. Figures 12 through 15 display the Orientation data recorded in each AIM. In addition to the orientation data we have again included the significant wave height recorded by each AIM. The most significant orientation changes correspond to periods of high significant wave height. Both AIM #2 and #4 were installed in a general East/West orientation and after the first two periods of increased significant wave height appear to have stabilized and the orientation remained constant. AIM #1 and #3 which had been installed in a general North/South orientation moved during the third storm (high significant wave height). Interestingly each mine of each set (the North/South and East/West) rolled in opposite directions. AIM 1 made only slight changes in the heading (less than 5 degrees during the entire deployment) that correspond with periodic increases in the significant wave height. Changes in heading were accompanied with rapid changes in pitch and a significant roll (up to 30°). The data suggest significant wave heights greater than 2 m cause scour around the mine. After a significant amount of scour occurs the mine begins to pitch and rolls into the scour pit changing heading to align with the swell.

Table 2 provides the orientation of the non-instrumented mines upon deployment and recovery as noted by the divers. The mines remained generally oriented in the same direction as deployed with the largest variation noted with the Rockan which was probably due to it's light weight and wedge shape.

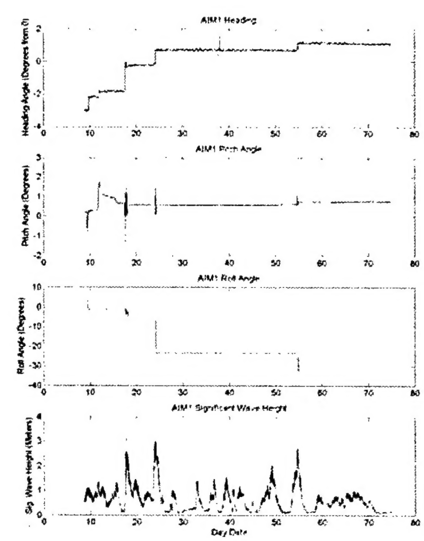

Fig. 12. Heading, Roll, Pitch and Significant Wave Height for AIM #1.

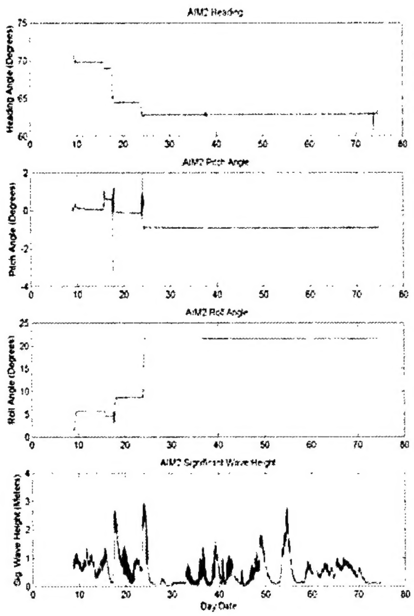

Fig. 13. Heading, Roll, Pitch and Significant Wave Height for AIM #2.

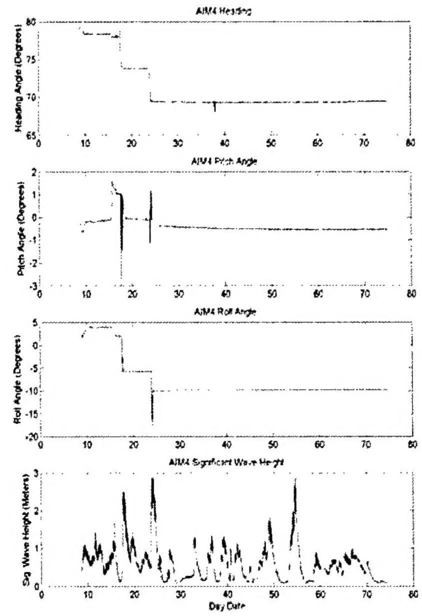

Fig. 15. Heading, Roll, Pitch and Significant Wave Height for AIM #4.

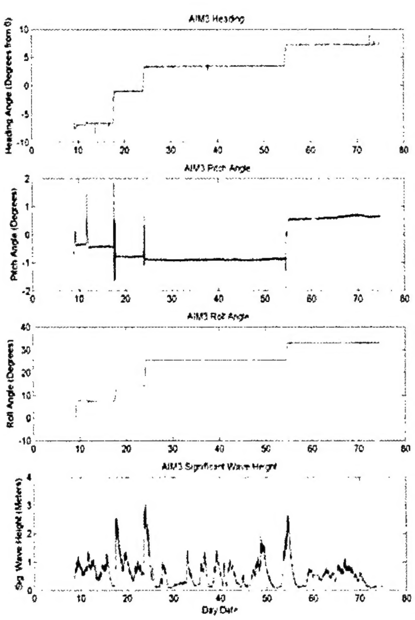

Fig. 14. Heading, Roll, Pitch and Significant Wave Height for AIM #3.

Table 2. Diver observations of non-instrumented mines.

Mine	Deployed Orientation	Recovered Orientation
FWG # 5	N-S	N-S
FWG # 6	E-W	≈ E-W (345°)
FWG # 7	N-S	N-S
FWG # 8	E-W	E-W (240°)
FWG # 9	E-W	E-W
FWG # 10	N-S	≈ N-S (20°)
Rockan # 13	330°	120°
Rockan # 14	315°	not given
Bomb # 15	200°	N-S (pointed S)
Bomb # 16	110°	E-W (pointed E)

VII. BURIAL

Estimated burial, relative to the water-sediment interface, of the AIMs was calculated by subtracting nearby NOAA recorded water depth from the AIMs recorded water depth/pressure (Fig. 16 through 19). The data collected with the 112 acoustic burial sensors (percent volume covered) is presently being processed and analyzed. Burial of the AIMs changed very little (maximum burial about 10 cm) until about day date 18 when the significant wave heights increased substantially (2.5 to 3 m - storm event 1) and all mines exhibited pitch and roll motion and changed heading. On the North/South oriented mines (#1 and #3) burial increased to about 40 cm (which is nearly 75% of the AIMs diameter). On the East/West oriented mines (#2 and #4) burial increased to about 30 cm (which is nearly 56% of the AIMs diameter). Note that the experiments began on day date 8 (January 8^{th}) therefore day date 18 is approximately 10 days after the experiments began. A second storm with significant wave heights (2.5 to 3.0 m - storm event 2) on day date 24-25 is correlated with additional mine movement of all four AIMS and the complete burial, relative to the water-sediment interface, of all four AIMs. After day date 25 only the North/South oriented mines (#1 and #3) exhibited any motion and this was correlated with a storm on day date 55. After the initial two significant scour events, around the AIMs, additional scour was not sufficient to cause a notable increase in burial. Tidal and wave action was in a East/West direction and it is possible that this contributed to greater scour action noted around the North/South oriented mines (#1 and #3) as indicated by the greater burial noted on storm event 1.

Burial, percent volume covered, recorded by the FWG mines exhibits similar trends to the AIMs with increasing in burial occurring during storm events. The percent burial however never exceeded 50% of the sensors covered. This data suggests that although mines buried to almost their full diameter (50 cm) the scour pits were never completely filled and greater than 50% of the surface area of the mines remained exposed. This scenario for burial is supported by both diver and ROV video camera observations of the mines. Figure 19 displays the FWG mine recorded burial, percent volume covered.

The FWG mines recorded three phases of burial. The events (1) 23/24 Jan (30 hours) and (2) 22/23 Feb (27 hours) were recorded by all six mines whereas event (3) on 17 Jan (12 hours) was recorded only by five mines and the sixth did not show any variation of burial. The maximum roll recorded by FWG mines was 15° and 20° respectively, in most cases roll was well below 10° during the events.

Figures 21 and 22 [7] are multibeam bathymetry that depicts AIM #4, FWG #8 and Rockan #14 only days prior to recovery. Figures 23 and 24 are photographs of AIM #4 and FWG #8 taken the day of recovery. Both the multibeam bathymetry and photographs clearly show the scour pits at each end of AIM #4 as well as the ripples transecting FWG #8.

Table 3 lists the diver observed burial (both relative to water-sediment interface and volume covered) of the mines just prior to recovery. The mines placed on coarse sediment tended not to bury, relative to the water-sediment interface, compared to similar shapes placed on fine sand. The Manta (#11) deployed at the coarse sand site did not bury, whereas the Manta (#12) deployed at the fine sand site buried 85%. The Rockan (#13) deployed at the coarse sand site did not bury, whereas the Rockan (#14) deployed at the fine sand site buried 50%. The Bomb (#15) deployed at the coarse sand site did not bury, whereas the Bomb (#16) deployed at the fine sand site buried 50%. The two FWG mines on coarse sand (#8 and #9) only buried 25% and 35% compared to no less than 50% for any of the other FWG mines on fine sand. It appears probable that the coarse sand was not easily eroded preventing scour around the mines which would have contributed to burial relative to the water-sediment interface.

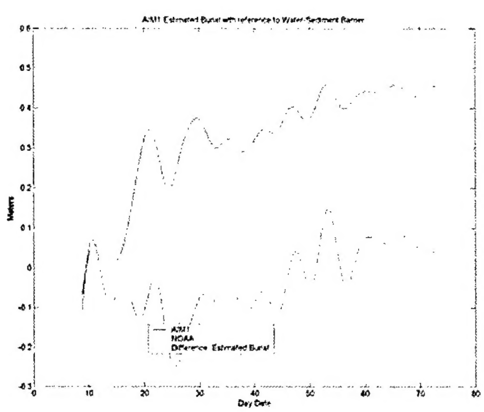

Fig. 16. Burial AIM#1.

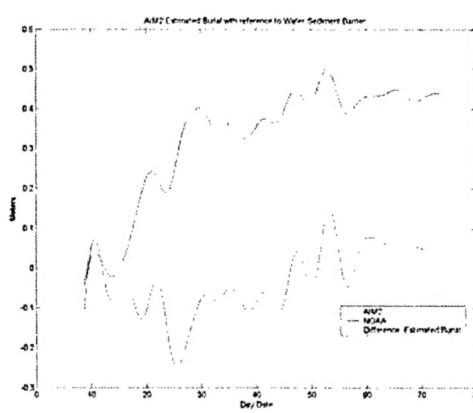

Fig. 17. Burial AIM#2.

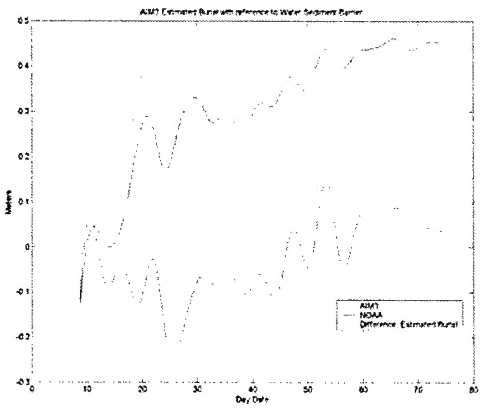

Fig. 18. Burial AIM#3.

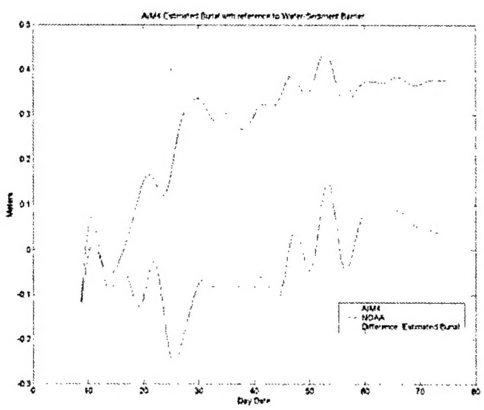

Fig. 19. Burial AIM#4.

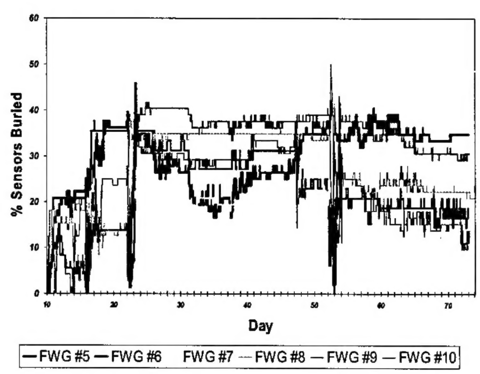

Fig. 20. Burial FWG Instrumented Mines.

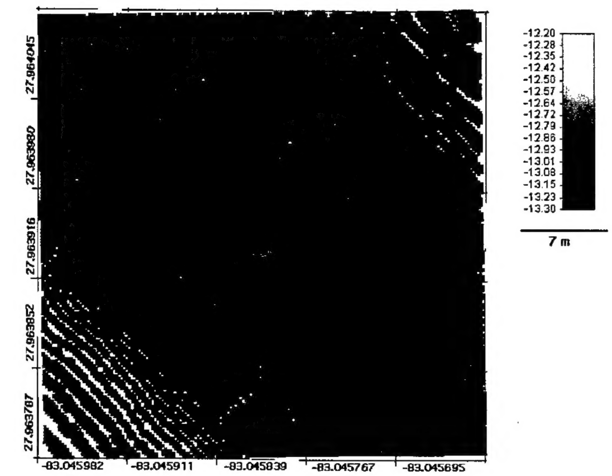

Fig. 21. Multibeam bathymetry of AIM #4 the day prior to recovery. Note the scour around AIM 4 is most prominent on the east and west ends of the mine. The Rockan mine is just visible within the scour pit that has formed around it. The color bar represents a depth range of 1.1 meters, and the scale bar denotes 7 meters. Data has been tide corrected to MLLW, and is gridded to 20 X 20 cm.

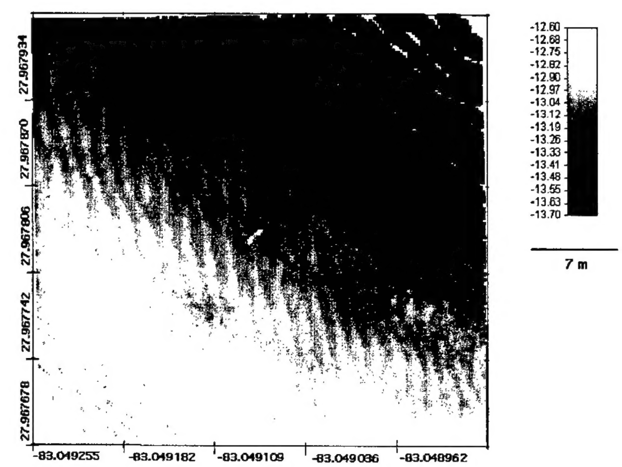

Fig. 22. Multibeam bathymetry of FWG #8 three days prior to recovery. The FWG 8 mine is just visible within the coarse sediment ripple field. Scour has occurred around the mine as evidenced by the interruption in the ripple pattern. Note that the seafloor is sloping off to the northeast and the NNW-SSE ripples have a median wavelength of 1.5 m and a mean of 1.4 ± 0.4 m and ~ 0.1 ± 0.02 m in amplitude. The color bar represents a depth range of 1.1 meters, and the scale bar denotes 7 meters. Data has been tide corrected to MLLW, and is gridded to 20 X 20 cm.

Table 3. Diver observed burial of mines at recovery (14 - 16 March 2003).

Mine	% Below Sediment Water Interface	% Covered with Sediment
Site 1 - Fine Sand Sediment		
AIM #1	75	not given
AIM #2	75	57
AIM #3	100	not given
AIM #4	100	75
FWG # 5	80	30
FWG # 6	90	20
Manta # 12	85	10
Rockan # 14	50	10
Bomb # 16	Varied ≈ 50	25
Site 2 - Coarse Sand Sediment		
FWG # 7	35	30
FWG # 8	25	30
Manta # 11	0	0
Rockan # 13	0	0
Bomb # 15	0	10
Site 3 - Fine Sand Sediment		
FWG # 9	50	20
FWG # 10	90	20

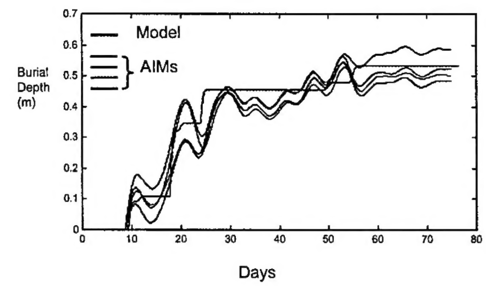

Fig. 23. Comparison of forecast for scour induced burial of cylindrical model to actual AIMs burial.

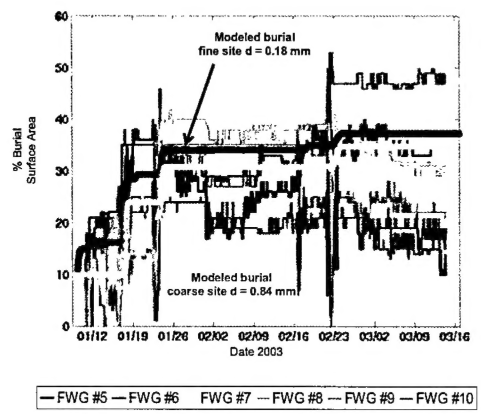

Fig 24. Comparison of forecast scour induced burial of cylindrical model to actual FWGs burial

VIII. BURIAL PREDICITION

The extensive sediment (USF and NRL) data combined with predictions from NOAA Wave Watch III wave forecast model was used to predict burial by wave-induced scour (A. Trembanis et. al. Sixth International Symposium on Technology and the Mine Problem). Figures 23 and 24 display the comparison of forecast models to the actual AIMs and FWGs burial. Note that the best model fit is based on the assumption that the scour pit does not infill. Extensive wave and current data collected with bottom mounted tripods compared favorably to physical oceanographic model predictions. Time-dependent scour measured using the optical and acoustic mines, characterized by sector scan sonar (USF), ROV video (USF), and diver photographs and observations (USF and NRL) compared favorably to model predictions.

IX. SUMMARY

Results of this experiment indicate that measured and predicated burial was greater on the fine sand compared to the coarse sand site. Burial episodes occurred during storms when significant weight height was highest. The wave induced scour model based on Whitehouse-Soulsby equations [8] adequately predicated time rate mine burial for the cylindrical mines at the fine sand site but seems to over predict burial at the coarse sands sites. Burial measured as mine height below the unaffected sediment surface around the mine was greater than measured as the surface area exposed (sensors covered) of the mines resting inside the scour craters. It is believed that the local orbital velocity of the water in the near field of a mine shape is increased and directed by the presence of the mine causing local erosion. Hence the development of scour pits forming around the mines and the lack of these pits filling in (no erosion apparently occurred outside the near field of the mine explaining the lack of sediment to fill in the scour pits). The larger objects buried deeper than the smaller objects.

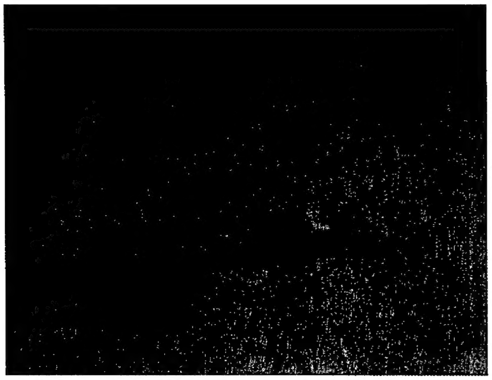

Fig. 25. AIM #4 at Recovery

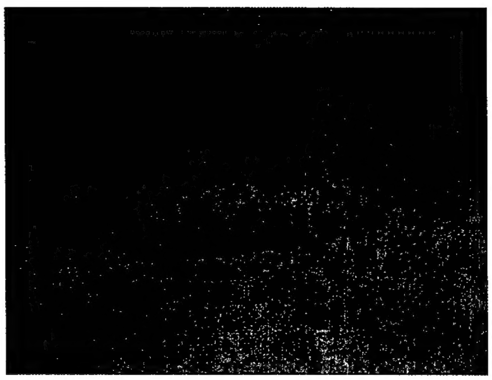

Fig. 26. FWG #8 at Recovery

ACKNOWLEDGEMENTS

The captain and crew of the R/V SUNCOASTER exhibited excellent seamanship for both the deployment and recovery of all the equipment. The divers Ricky Ray, Robert Fisher, Robert Brown, Chad Vaughan, expertly positioned the equipment on the seafloor, made detailed observations and recovered many samples.

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